

Belle $J/\psi + \eta_c$ anomaly and a very light scalar boson

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Abstract

The large rate of the $J/\psi + \eta_c$ production observed by the Belle collaboration has posed a serious challenge to our understanding of the quarkonium. We examine a scenario that there exists a light scalar boson around 5 GeV, with an enhanced coupling solely to the charm quark. Such a scenario would explain the Belle anomaly. It also predicts a significant increase in J/ψ plus open charm pair production. An immediate test for the scalar boson is to look for a peak around 5 GeV in the recoil mass spectrum of J/ψ , because the scalar boson can also be produced in association with the J/ψ . Finally, we also point out that the process $e^+e^- \rightarrow H\gamma$ is sizable for observation.

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I. INTRODUCTION

The best understood QCD system is perhaps the heavy quarkonium, made up of heavy quark and antiquark. Known systems include charmonium, bottomonium, and B_c mesons. We thought we understand these systems, but surprises often come up as more and more data become available. A well-known incident was the surplus of J/ψ produced at high transverse momentum at the Tevatron [1]. The color-singlet model [2] missed the cross section by more than an order of magnitude. The color-octet mechanism [3] and subsequently the nonrelativistic QCD model [4] were formulated to explain the surplus.

Recently, the Belle Collaboration observed double charmonium production, namely, $J/\psi + \eta_c$ at $\sqrt{s} = 10.6$ GeV [5]. The production rate is anomalous [5, 6, 7]

$$\begin{aligned} \sigma(e^+e^- \rightarrow J/\psi \eta_c) &\times B(\eta_c \rightarrow 2 \text{ charged}) \\ &= (0.033^{+0.007}_{-0.006} \pm 0.009) \text{ pb}, \end{aligned}$$

which is roughly an order of magnitude larger than any QCD predictions [8]. It poses a strong threat to our understanding of quarkonium. However, one has to note that the J/ψ is detected via its leptonic decay while η_c is inferred from the recoil mass spectrum of the J/ψ . Therefore, the η_c is actually not identified, and perhaps it could be a J/ψ , or something else. Based on this argument, Bodwin, Lee, and Braaten [9] argued that Belle in fact observed double J/ψ 's, which are produced via double virtual photons. However, the further analysis by Belle does not seem to support this idea [6]. Thus, the anomalous production remains one of the challenging problems in QCD, and arouses speculations. For example, a heavy glueball of a mass very near m_{η_c} with a rather large matrix amplitude has been proposed[10] to account for the excess.

In this Letter, we study a possible scenario of the existence of a light scalar boson H , which has an enhanced coupling to the charm quarks. It contributes to both the $J/\psi + \eta_c$ production, and J/ψ plus open charm pair production. We show the allowed parameter space region of the mass of this scalar and the coupling to charm, fitted to the Belle data. We find that a coupling constant $g_H \approx 1$ and $m_H \approx 5$ GeV can fit the data well. An immediate test for this light scalar boson is to look for a peak around 5 GeV in the recoil mass spectrum of J/ψ , because this scalar can also be produced directly in association with a J/ψ . So far, the Belle collaboration has only shown the recoil mass spectrum with very

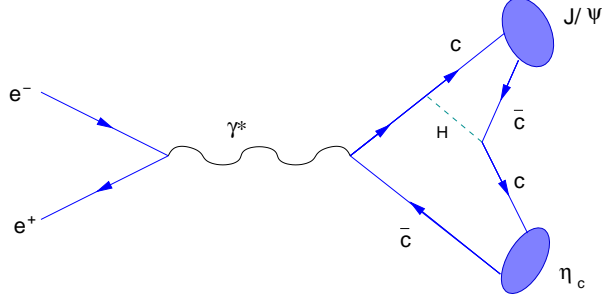


FIG. 1: One of the four contributing Feynman diagrams for $e^+e^- \rightarrow J/\psi \eta_c$ via an intermediate scalar boson H .

fine bin size up to 4 GeV [5, 6, 7], where η_c , χ_{c0} , and $\eta_c(2S)$ can be seen. However, the bin size in the region above 4 GeV is too large. Therefore, we urge the Belle collaboration to scan with very fine steps in the region above 4 GeV. (Even with a large bin size, we notice that there may be something peculiar at around 5.2–5.4 GeV bins [5, 6].) Finally, we point out that another process $e^+e^- \rightarrow H\gamma$, which is negligible within the SM, becomes sizable in the our scenario. This is another interesting test for the scenario.

II. $e^+e^- \rightarrow J/\psi \eta_c$

Suppose the interaction of the scalar boson H with the charm-quark pair is given by

$$\mathcal{L} = -g_H \bar{c} c H, \quad (1)$$

with a coupling constant g_H that will be determined later.

Assuming that the scalar decays into a $c\bar{c}$ pair only, the width of H is given by

$$\Gamma_H = \frac{3}{8\pi} g_H^2 m_H \left[1 - \frac{4m_c^2}{m_H^2} \right]^{3/2}. \quad (2)$$

For $m_H \sim 5$ GeV and $g_H \sim 1$, the $\Gamma_H \sim 0.06m_H$, which is narrow compared with its mass but much wider than the widths of J/ψ and η_c . In the following, we use the Breit-Wigner prescription for the scalar boson propagator.

One of the contributing Feynman diagrams for $e^+e^- \rightarrow J/\psi \eta_c$ is shown in Fig. 1. The sum of the amplitudes of the four contributing Feynman diagrams for $e^-(p_1)e^+(p_2) \rightarrow$

$J/\psi(k_1)\eta_c(k_2)$ is given by

$$i\mathcal{M} = -4g_H^2 e^2 Q_e Q_c \frac{R_\psi(0)R_{\eta_c}(0)}{\pi} \frac{1}{s^2} \frac{1}{s/4 - m_H^2 + i\Gamma_H m_H} \\ \times \bar{v}(p_2)\gamma^\mu u(p_1) \epsilon_{\mu\rho\lambda\sigma} k_2^\rho k_1^\sigma \epsilon^\lambda(k_1) \quad (3)$$

where $\epsilon(k_1)$ is the polarization 4-vector of the J/ψ , and s is the square of the center-of-mass energy of the collision. $R_\psi(0)$ and $R_{\eta_c}(0)$ are the wavefunctions at the origin, with the normalization $\int_0^\infty |R(r)|^2 r^2 dr = 1$. Here the center-of-mass energy \sqrt{s} of the collision is at 10.6 GeV, and so we simply only take the intermediate photon approximation (the intermediate Z contribution is suppressed by $s/m_Z^2 \sim 0.013$.)

The angular distribution of the process is given by

$$\frac{d\sigma}{d\cos\theta} = \alpha^2 g_H^4 Q_e^2 Q_c^2 \frac{|R_\psi(0)|^2 |R_{\eta_c}(0)|^2}{\pi} \frac{1}{s^2} \\ \times \frac{1}{(s/4 - m_H^2)^2 + \Gamma_H^2 m_H^2} \beta^3 (1 + \cos^2\theta), \quad (4)$$

where

$$\beta = \sqrt{\left(1 - \frac{m_\psi^2}{s} - \frac{m_{\eta_c}^2}{s}\right)^2 - 4 \frac{m_\psi^2}{s} \frac{m_{\eta_c}^2}{s}}.$$

Integrating the angle we obtain the total cross section

$$\sigma = \frac{8}{3} \alpha^2 g_H^4 Q_e^2 Q_c^2 \frac{|R_\psi(0)|^2 |R_{\eta_c}(0)|^2}{\pi} \frac{1}{s^2} \\ \times \frac{1}{(s/4 - m_H^2)^2 + \Gamma_H^2 m_H^2} \beta^3 \quad (5)$$

Let us examine the allowed parameter space of m_H and g_H that can fit the Belle cross section. Combining the systematic and statistical errors of the Belle data the 1σ range is 0.033 ± 0.011 pb. We show the contours of the central value, $\pm 1\sigma$, and $\pm 2\sigma$ in Fig. 2. Taking $g_H = 1$ the allowed central value (2σ range) for m_H is

$$m_H = 5.10 (4.87 - 5.20) \text{ GeV} \text{ or } 5.45 (5.36 - 5.66) \text{ GeV}. \quad (6)$$

Here we used $|R_\psi(0)|^2 = |R_{\eta_c}(0)|^2 = 0.8 \text{ GeV}^3$.

It is straightforward to adapt our scenario to explain other peaks in the recoil mass spectrum between 3 – 3.8 GeV, i.e. χ_{c0} and $\eta_c(2S)$ [5, 6]. Since our scenario only requires the m_H at around $\sqrt{s}/2$, it would also explain the enhancement to the production of $J/\psi + (\eta_c(1S), \chi_{c0}, \eta_c(2S))$. Note that our scenario would not give enhancement

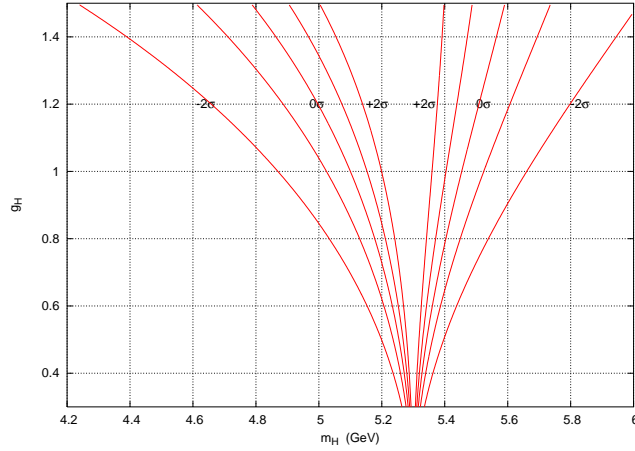


FIG. 2: The $\pm 1\sigma$ and $\pm 2\sigma$ bound for the (m_H, g_H) plane due to the Belle data of 0.033 ± 0.011 pb.

to $J/\psi + (J/\psi, \chi_{c1}, \chi_{c2}, \psi(2S))$ because of the spin-parity-charge-conjugation of the photon propagator. This is in agreement with the observation by Belle [6].

Note that if we choose a smaller g_H , the corresponding central value m_H of the fit to the Belle data would become closer to $\sqrt{s}/2 = 5.3$ GeV, and the 2σ range would also become smaller, as shown in Fig. 2. The smaller the value of g_H , the more fine-tuned value for m_H that the fit gives. So in the following predictions of our scenario we simply take $g_H = 1$ and the results just scale as some powers of g_H .

If we replace the scalar H by a pseudoscalar boson A^0 , the diagram similar to Fig. 1 with H replaced by A^0 gives vanishing amplitude in the static approximation. There is another diagram with the virtual A^0 bremsstrahlung off the charm quark turning into the η_c state. However, such a contribution is important only when the mass m_{A^0} is around $3 - 4$ GeV, which is unfavorable based on the constraint of the Belle search.

The static approximation of using the wavefunction at the origin may not be so valid when the Higgs pole is involved, however our simple calculation serves the purpose of estimating of the size of the production rate due to the light Higgs boson H .

III. $e^+e^- \rightarrow J/\psi c\bar{c}$

This process is very similar to the original $J/\psi + \eta_c$ production, except that the $c\bar{c}$ pair does not form a bound state but goes into an open pair. They will hadronize into D mesons.

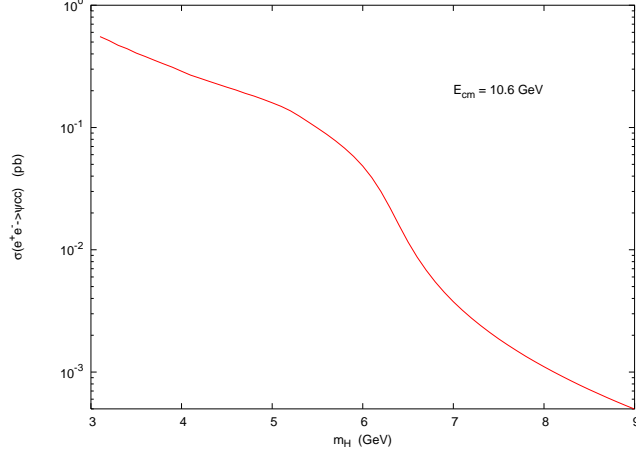


FIG. 3: The production cross section for $e^+e^- \rightarrow J/\psi c\bar{c}$ Vs m_H . The value of $g_H = 1$ is chosen.

The calculation is straightforward, but however the result is not simple enough to be put here. We show the cross section verse m_H at $\sqrt{s} = 10.6$ GeV in Fig. 3. The cross section scales as g_H^4 . At $m_H \simeq 5$ GeV, $\sigma(e^+e^- \rightarrow J/\psi c\bar{c}) \approx 0.15$ pb for $g_H = 1$. Therefore, it contributes substantially to J/ψ + open charm production.

IV. $e^+e^- \rightarrow \psi H$

The sum of the two Feynman diagrams of the process $e^-(p_1)e^+(p_2) \rightarrow \psi(k_1)H(k_2)$ is given by

$$i\mathcal{M} = 2\sqrt{3}e^2Q_eQ_cg_H \frac{R_\psi(0)}{\sqrt{\pi m_\psi}} \frac{1}{s} \frac{1}{s - m_\psi^2 + m_H^2} \\ \times \bar{v}(p_2)\gamma_\mu u(p_1) [(s - m_H^2 + m_\psi^2)\epsilon^\mu(k_1) - 2k_2 \cdot \epsilon(k_1)k_1^\mu]$$

The differential cross section is

$$\frac{d\sigma}{d\cos\theta} = 6\alpha^2 g_H^2 Q_e^2 Q_c^2 \frac{|R_\psi(0)|^2}{m_\psi} \frac{1}{(s - m_\psi^2 + m_H^2)^2} \beta \\ \times \left[4\frac{m_\psi^2}{s} + \frac{1}{2}\beta^2(1 + \cos^2\theta) \right] \quad (7)$$

where

$$\beta = \sqrt{\left(1 - \frac{m_\psi^2}{s} - \frac{m_H^2}{s}\right)^2 - 4\frac{m_\psi^2}{s}\frac{m_H^2}{s}}$$

The integrated cross section is

$$\sigma = 6\alpha^2 g_H^2 Q_e^2 Q_c^2 \frac{|R_\psi(0)|^2}{m_\psi} \frac{1}{(s - m_\psi^2 + m_H^2)^2} \beta \left[8\frac{m_\psi^2}{s} + \frac{4}{3}\beta^2 \right] \quad (8)$$

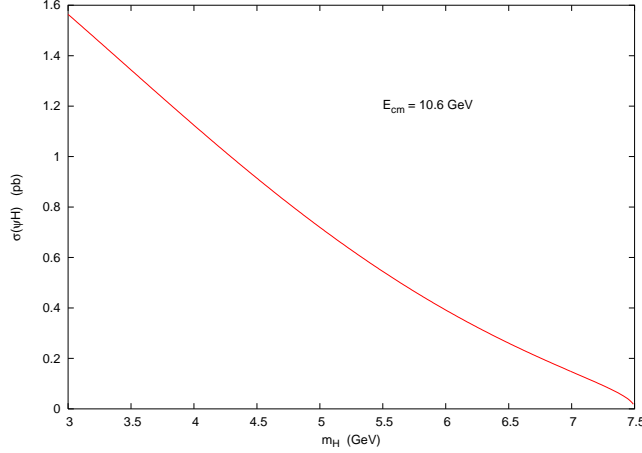


FIG. 4: The production cross section for $e^+e^- \rightarrow J/\psi H$ Vs m_H . The value of $g_H = 1$ is chosen.

In Fig. 4, we show the production cross section of $\sigma(\psi H)$ with $g_H = 1$. The cross section scales as g_H^2 . The scalar boson H so produced is heavy enough to decay into an open charm-quark pair. Thus, it will give rise to open charm pair production, with the pair around 5 GeV. If the Belle could scan the recoil mass spectrum of J/ψ further up to 5 – 6 GeV, they should be able to see if this scalar boson H exists. This is the most immediate test for the scenario.

V. $e^+e^- \rightarrow H\gamma$

In the SM, the leading contribution to the process $e^+e^- \rightarrow H\gamma$ comes from the one-loop diagrams with the W boson and heavy fermions running in the loop. In our scenario with H coupling strongly to charm, this channel could be sizable for detection. The SM calculation was completed in Ref. [11]. We use its formulas with the charm-quark contribution only, and modify the SM coupling to our enhanced coupling as follows:

$$\sqrt{2}G_F m_c^2 \rightarrow g_H^2.$$

We show the ratio of $\sigma(e^+e^- \rightarrow H\gamma)/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ at $\sqrt{s} = 10.6$ GeV for $m_H = 3 - 9$ GeV with $g_H = 1$ in Fig. 5. The ratio scales as g_H^2 . Note that with the SM coupling strength ($gm_c/2m_W$), this ratio is very small, of order $O(10^{-9})$. With the enhanced charm coupling, the ratio is of order 5×10^{-5} for $m_H = 5$ GeV. Thus, the cross section of $e^+e^- \rightarrow H\gamma$ for $m_H = 5$ GeV at $\sqrt{s} = 10.6$ GeV is about 40 fb, which will give thousands of events at Belle

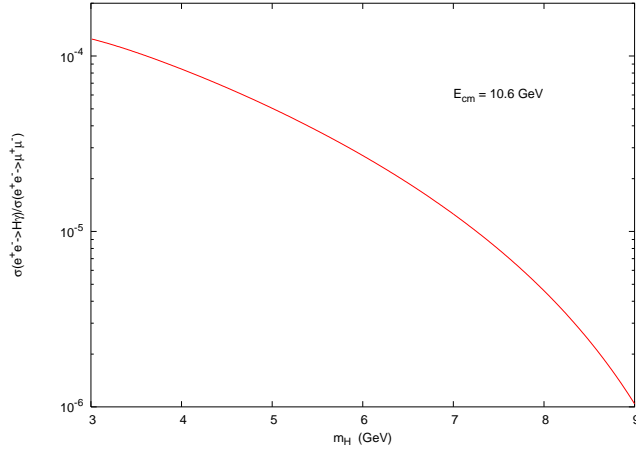


FIG. 5: The ratio of $\sigma(e^+e^- \rightarrow H\gamma)/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ at $\sqrt{s} = 10.6$ GeV for $m_H = 3 - 9$ GeV. The scenario is $g_H = 1$.

or BaBar with an integrated luminosity of 100 fb^{-1} .

VI. DISCUSSION

One may concern about the high energy analog of $e^+e^- \rightarrow c\bar{c}H$ production. In high energy collisions, we would expect extra $c\bar{c}c\bar{c}$ in the final state, with one of the $c\bar{c}$ pairs clustering at around 5 GeV. To our knowledge there have not been any measurement on four-charm production, nor any searches explicitly looking for anomalous four-charm events at LEP or at the Tevatron. There were perhaps some mysterious 4-jet events recorded by ALEPH [12], but it had no explicit identification of charm in those events. Also, the search for four-charm events suffers severely from the weak charm identification, which is, to some extent, overlapped with the b-quark identification. Therefore, there is no explicit constraints on four-charm production coming from high energy experiments.

Another possible source of constraints comes from Upsilon $\Upsilon(1S)$ decays. From the Particle Data Book [13], the branching ratio $B(\Upsilon(1S) \rightarrow J/\psi + X) = 1.1 \pm 0.4\%$. Given such a large error it is impossible to rule out our scenario, because $J/\psi + \eta_c$, $J/\psi + H$, or $J/\psi +$ open charm could only give a branching ratio below 0.4%. There is also a limit on $B(\Upsilon \rightarrow \gamma + X) < 3 \times 10^{-5}$, where X is a pseudoscalar boson. In our scenario, we have a scalar boson and so the limit is not directly applicable. Even so, $B(\Upsilon \rightarrow H\gamma)/B(\Upsilon \rightarrow \mu^+\mu^-)$ would be very similar to $\sigma(e^+e^- \rightarrow H\gamma)/\sigma(e^+e^- \rightarrow \mu^+\mu^-) \approx 5 \times 10^{-5}$ (from Fig. 5) without

an explicit calculation. It implies $B(\Upsilon \rightarrow \gamma + H) \approx 10^{-6}$, which is well below the existing limit that we stated above.

The anomalous double charmonium $J/\psi + \eta_c$ production measured by Belle posed a very strong challenge to our understanding of QCD. We have investigated the scenario of a light scalar boson of mass about 5 GeV with a large coupling (of order the weak coupling or even larger) to the charm quark. We found that it could explain the $J/\psi + \eta_c$ anomaly, and provided the much-needed J/ψ plus open charm production. It would also explain the enhancement to the production of $J/\psi + (\eta_c(1S), \chi_{c0}, \eta_c(2S))$, but not to $J/\psi + (J/\psi, \chi_{c1}, \chi_{c2}, \psi(2S))$ because of the spin-parity-charge-conjugation of the photon propagator. This is in agreement with the observation by Belle. An immediate test for this light scalar boson is to scan the recoil mass spectrum of J/ψ and look for a peak around 5 GeV, because this scalar can also be produced directly in association with a J/ψ . So far, the Belle collaboration has only shown the recoil mass spectrum with very fine bin size up to 4 GeV [5, 6], where η_c, χ_{c0} , and $\eta_c(2S)$ can be seen. However, the bin size in the region above 4 GeV is too large. We, therefore, urge the Belle collaboration to scan the recoil mass spectrum with very fine bin size above 4 GeV. (Even with a large bin size, we notice that there may be something peculiar at around 5.2–5.4 GeV bins [5, 6], but this is only our wild guess.) Finally, we have pointed out that another process $e^+e^- \rightarrow H\gamma$, which is negligible within the SM, becomes sizable in the new scenario of a light scalar boson, which couples strongly to charm. This is another test for the scenario.

One may ask where this scalar boson comes from. Such a light Higgs may come from the general form of the multi-Higgs doublet sector. The required enhanced coupling to the charm quark implies dedicated fine tuning. It also requires additional fine tuning to kill the unwanted flavor changing neutral processes. If we stay within the scope of the two-Higgs doublet sectors with the quark couplings like those in the minimal supersymmetric standard model, the coupling strength of H to charm is $gm_c \cot \beta / 2m_W$. Therefore, in order to have an effective coupling $g_H \sim g$ we need a $\cot \beta \sim 2m_W / m_c \sim O(100)$. Such a large $\cot \beta$ is unnatural and perhaps causes a big problem to the top Yukawa coupling. We do not offer a good answer to the structure of the Higgs sector in this paper.

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